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(54) MONOOXYGENASES A CYTOCHROME P450 MODIFIED

(54) MODIFIED CYTOCHROME P450 MONOOXYGENASES

(57)

The invention relates to modified cytochrome P450 monooxygenases comprising a modified substrate profile, to nucleic acid sequences that code therefor, to expression constructs and vectors, and to recombinant microorganisms which contain these vectors. The invention also relates to methods for microbiologically producing terminally or subterminally hydroxylated aliphatic carboxylic acids.





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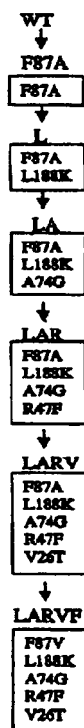
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(54) Title: MODIFIED CYTOCHROME P450 MONOOXYGENASES



(57) Abrégé/Abstract:

The invention relates to modified cytochrome P450 monooxygenases comprising a modified substrate profile, to nucleic acid sequences that code therefor, to expression constructs and vectors, and to recombinant microorganisms which contain these

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vectors. The invention also relates to methods for microbiologically producing terminally or subterminally hydroxylated aliphatic carboxylic acids.

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(54) Title: MODIFIED CYTOCHROME P450 MONOOXYGENASES

(54) Bezeichnung: MODIFIZIERTE CYTOCHROM P450-MONOOXYGENASEN

(57) Abstract: The invention relates to modified cytochrome P450 monooxygenases comprising a modified substrate profile, to nucleic acid sequences that code therefor, to expression constructs and vectors, and to recombinant microorganisms which contain these vectors. The invention also relates to methods for microbiologically producing terminally or subterminally hydroxylated aliphatic carboxylic acids.

(57) Zusammenfassung: Die vorliegende Erfindung betrifft modifizierte Cytochrom P450-Monooxygenasen mit verändertem Substratprofil, dafür kodierende Nukleinsäuresequenzen, Expressionskonstrukte und Vektoren, rekombinante Mikroorganismen, welche diese Vektoren enthalten sowie Verfahren zur mikrobiologischen Herstellung terminal oder subterminal hydroxylierter aliphatischer Carbonsäuren.



WO 01/07574 A3

Modified cytochrome P450 monooxygenases

The present invention relates to modified cytochrome P450 monooxygenases with an altered substrate profile, to nucleic acid sequences coding therefor, to expression constructs and vectors, to recombinant microorganisms which comprise these vectors, and to processes for the microbiological production of terminally or subterminally hydroxylated aliphatic carboxylic acids.

10 The monooxygenase with the name P450 BM-3 is a cytochrome P450 enzyme from *Bacillus megaterium* and has a pronounced sequence homology with mammalian P450 enzymes (1). Owing to these correspondences, P450 BM-3 constitutes an excellent model system
15 for this class of P450 enzymes. P450 BM-3 hydroxylates mainly long-chain saturated fatty acids on their ω -1, ω -2 and ω -3 carbon atom. Amides or alcohol analogs and epoxides of long-chain unsaturated fatty acids are also converted (1-3). The catalytic activity for saturated fatty acids depends on the chain length,
20 the chain length optimum being 14 to 16 carbon atoms. The enzyme shows no catalytic activity for fatty acids with a chain length of less than 12 carbon atoms (1).

Summary of the invention

25 It is an object of the present invention to provide cytochrome P450 monooxygenase mutants which show a modified substrate profile in comparison with the wild-type enzyme. In particular, it was an object to provide novel mutants which hydroxylate
30 saturated aliphatic carboxylic acids in another chain position and/or have a modified substrate specificity. In particular, it was an object to provide mutants which have a catalytic activity for aliphatic carboxylic acids of medium chain length, in particular with a chain length of 8 to 12, such as, for example,
35 8 to 10, carbon atoms, and which hydroxylate these carboxylic acids subterminally, especially at the positions ω -1, ω -2 and/or ω -3.

We have found that this object is achieved by providing modified
40 cytochrome P450 monooxygenases which, owing to a combination of directed evolution and site-specific mutagenesis of their substrate-binding region, show an altered reactivity pattern or substrate profile in the terminal and/or subterminal enzymatic hydroxylation of aliphatic carboxylic acids in comparison with
45 the wild type.

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Detailed description of the invention

Compared to the wild-type enzyme, an "altered substrate profile" is observed in mutants according to the invention. An "altered substrate profile" means, for the purposes of the present invention, a) an improved reactivity such as, for example, an increase in specific activity (expressed as nmol reacted carboxylic acid/minute/nmol P450-enzyme) and/or at least one kinetic parameter selected from amongst K_{cat} , K_m and K_{cat}/K_m , for example an improvement of at least 1%, such as, for example, 10 to 1000%, 10 to 500%, or 10 to 100%, of the mutant for at least one hydroxylatable aliphatic carboxylic acid or a hydroxylatable derivative of an aliphatic carboxylic acid, and/or b) an altered, in particular increased, regioselectivity in the hydroxylation of the carboxylic acid. There is thus, for example, a shift of the preferred terminal or subterminal (ω -1, ω -2, ω -3, ω -4, in particular ω -1 to ω -3) hydroxylation position at at least one hydroxylatable carboxylic acid or a hydroxylatable derivative of an aliphatic carboxylic acid. Hydroxylatable aliphatic carboxylic acids or derivatives thereof in which an "altered substrate profile" can be observed in accordance with the invention are branched or, preferably, straight-chain carboxylic acids having 8 to 30 carbon atoms. The alteration according to the invention of the substrate profile may be manifested over the entire length (i.e. C_8 - C_{30}) or only in sections, for example in the case of C_8 - C_{12} -, C_{10} - C_{12} -, C_{12} - C_{30} -, C_{12} - C_{25} - or C_{12} - C_{20} carboxylic acids or individual carboxylic acids from amongst these sections.

Nonlimiting examples which may be mentioned of carboxylic acids which can be hydroxylated in accordance with the invention are: caprylic acid, pelargonic acid, capric acid, undecanoic acid, lauric acid, tridecanoic acid, myristic acid, pentadecanoic acid, palmitic acid, margaric acid, stearic acid, nonadecanoic acid, arachidic acid, behenic acid, lignoceric acid, cerotic acid and melissic acid. Examples of suitable carboxylic acid derivatives are C_1 - C_4 -alkyl esters, amides or anhydrides with, preferably, short-chain C_1 - C_4 -carboxylic acids.

The monooxygenases according to the invention are preferably derived from cytochrome P450 monooxygenases from the enzyme class E.C. 1.14.--, in particular from the P450 family CYP102, and are of eukaryotic or prokaryotic, in particular bacterial, origin.

An especially preferred group of mutants is derived from *Bacillus megaterium* cytochrome P450 monooxygenase BM-3 with an amino acid sequence as shown in SEQ ID NO:2, which has at least one functional mutation in one of the following amino acid sequence

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regions: 24-28, 45-51, 70-72, 73-82 (helix 5), 86-88 (helix 6), 172-224 (F/G loop) and 352-356 (β -strand 8), with the proviso that, if the enzyme carries the mutation F87A, more than one of these regions is mutated; and functional equivalents of these 5 mutants.

In the present description, the mutation in question is shown in the amino acid one-letter code. The original amino acid is shown before the number which indicates the sequence position of the 10 mutation, while the modified amino acid is shown after the number.

A "functional mutation" for the purposes of the present invention encompasses an amino acid exchange in the abovementioned sequence 15 regions which results in an "altered reactivity pattern" or "altered substrate profile" in accordance with the above definition.

Especially preferred in accordance with the invention are P450 20 BM-3 monooxygenase mutants (group (A)) which comprise individually or in combination in at least each case one functional mutation in the amino acid sequence regions 86-88, 172-224, 73-82, 45-51 and 24-28 (in accordance with SEQ ID NO: 2).

25

Thus, for example, Phe87 may be replaced by an amino acid with an aliphatic side chain such as, for example, Ala, Val, Leu, in particular Val or Ala; Leu188 may be replaced by an amino acid with an amine or amide side chain such as, for example, Asn, Gln, 30 Arg or, in particular, Lys, or amino acids such as Ala, Gly, Ser and Trp; Ala74 may be replaced by another amino acid with an aliphatic side chain, such as, for example, Val and, in particular, Gly; Arg47 may be replaced by an amino acid with a cyclic side group such as, for example, His, Tyr or, in 35 particular, Phe; and Val26 can be replaced by an amino acid with a hydroxyl side group such as, for example, Ser or, in particular, Thr.

Preferred group (A) mutants exhibit at least one of the following 40 amino acid substitution patterns:

- a) F87V;
- b) F87A, L188K;
- c) F87V, L188K;
- 45 d) F87A, L188K; A74G;
- e) F87V, L188K, A74G;
- f) F87A, L188K, A74G, R47F;

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- g) F87V, L188K, A74G, R47F;
- h) F87A, L188K, A74G, R47F, V26T; or
- i) F87V, L188K, A74G, R47F, V26T;

5 and functional equivalents thereof.

A further group, group (B), of suitable mutants exhibits a single amino acid substitution in one of the abovementioned sequence regions or in one of the sequence regions 70-72 and 352-356. In
10 the two last-mentioned sequence regions, Ser72, for example, may be replaced by an amino acid with an aliphatic side chain such as, for example, Ala, Val, Leu, Ile and, in particular, Gly, and Met354 may be replaced by an amino acid with a hydroxyl side group such as, for example, Ser or, in particular, Thr.

15

In particular, mutants of group B exhibit an amino acid substitution from amongst the following:

- a) V26T,
- 20 b) R47F,
- c) S72G,
- d) A74G,
- e) F87V,
- f) L188z, where z is K, R, W, Q, N, G, A or S,
- 25 and
- g) M354T;

and functional equivalents thereof.

30 "Functional equivalents" are to be understood as meaning in accordance with the invention mutants which exhibit, in at least one of the abovementioned sequence positions, an amino acid substitution other than the one mentioned specifically, but still lead to a mutant which, like the mutant which has been mentioned
35 specifically, show an "altered substrate profile" in accordance with the above definition over the wild type. Functional equivalence exists in particular also in the case where the alternations in the reactivity pattern correspond qualitatively.

40 "Functional equivalents" naturally also encompass P450 monooxygenase mutants which, like the P450 BM3 mutants which have been mentioned specifically, can be obtained by mutating P450 enzymes from other organisms. For example, regions of homologous sequence regions can be identified by sequence comparison.

45 Following the principles of what has been set out specifically in the invention, the modern methods of molecular modeling then

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allow equivalent mutations to be carried out which affect the reaction pattern.

"Functional equivalents" also encompass the mutants which can be obtained by one or more additional amino acid additions, substitutions, deletions and/or inversions, it being possible for the abovementioned additional alterations to occur in any sequence position as long as they give rise to a mutant with an "altered substrate profile" in the above sense.

10

The present invention furthermore relates to nucleic acid sequences encoding a mutated monooxygenase or a "functional equivalent" in accordance with the above definition. These sequences can preferably be obtained from SEQ ID NO: 1 by codon exchange in accordance with the above amino acid substitution patterns.

The invention also encompasses those nucleic acid sequences which encompass so-called silent mutations or which are altered in comparison with a specifically mentioned sequence in accordance with the codon usage of a specific origin or host organism, and naturally occurring variants of such nucleic acid sequences. Also encompassed by the invention are deviations of the nucleic acid sequences obtained by the degeneracy of the genetic code (i.e. without altering the corresponding amino acid sequence) or by conservative nucleotide substitution (i.e. the corresponding amino acid is replaced by another amino acid with the same charge, size, polarity and/or solubility), and also sequences altered by the addition, insertion, inversion or deletion of nucleotides and which encode a monooxygenase according to the invention with an "altered substrate profile", and the corresponding complementary sequences.

The invention furthermore relates to expression constructs comprising a nucleic acid sequence encoding a mutant according to the invention under the genetic control of regulatory nucleic acid sequences; and vectors encompassing at least one of these expression constructs.

Preferably, the constructs according to the invention encompass a promoter 5'-upstream and a terminator sequence 3'-downstream of the encoding sequence in question, and, if appropriate, other customary regulatory elements, in each case operatively linked with the encoding sequence. Operative linkage is to be understood as meaning the sequential arrangement of promoter, encoding sequence, terminator and, if appropriate, other regulatory elements in such a manner that each of the regulatory elements

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can fulfill its intended function on expression of the encoding sequence. Examples of operatively linkable sequences are targeting sequences, or else translation enhancers, polyadenylation signals, selection markers, amplification
5 signals, replication origins and the like.

In addition to the artificial regulatory sequences, the natural regulatory sequence can still be present upstream of the actual structural gene. If desired, this natural regulation may also be
10 switched off by genetic alteration, and the expression of the genes may be enhanced or lowered. However, the gene construct may also be simpler in construction, i.e. no additional regulatory signals are inserted upstream of the structural gene and the natural promoter with its regulation is not removed. Instead, the
15 natural regulatory sequence is mutated in such a way that regulation no longer takes place and the gene expression is increased or reduced. One or more copies of the nucleic acid sequences may be present in the gene construct.

20 Examples of promoters are: cos, tac, trp, tet, trp-tet, lpp, lac, lpp-lac, lacIq, T7, T5, T3, gal, trc, ara, SP6, l-PR or l-PL promoter, all of which are advantageously employed in Gram-negative bacteria; and the Gram-positive promoters amy and SPO2, the yeast promoters ADC1, MFA, AC, P-60, CYC1, GAPDH or the
25 plant promoters CaMV/35S, SSU, OCS, lib4, usp, STLS1, B33, nos, or the ubiquitin or phaseolin promoter.

In principle, all natural promoters with their regulatory sequences can be used. In addition, synthetic promoters may also
30 be used in an advantageous fashion.

The abovementioned regulatory sequences are intended to allow the directed expression of the nucleic acid sequences. Depending on the host organism, this may mean, for example, that the gene is
35 expressed or overexpressed only after induction has taken place, or that it is expressed and/or overexpressed immediately.

The regulatory sequences or factors can preferably have a positive effect on expression and in this manner increase or
40 reduce the latter. Thus, an enhancement of the regulatory elements may advantageously take place at the transcriptional level by using strong transcription signals such as promoters and/or "enhancers". In addition, translation may also be enhanced by improving, for example, mRNA stability.

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An expression cassette is generated by fusing a suitable promoter with a suitable monooxygenase nucleotide sequence and a terminator signal or polyadenylation signal. To this end, customary recombination and cloning techniques are used as they are described, for example, by T. Maniatis, E.F. Fritsch and J. Sambrook, *Molecular Cloning: A Laboratory Manual*, Cold Spring Harbor Laboratory, Cold Spring Harbor, NY (1989) and by T.J. Silhavy, M.L. Berman and L.W. Enquist, *Experiments with Gene Fusions*, Cold Spring Harbor Laboratory, Cold Spring Harbor, NY (1984) and by Ausubel, F.M. et al., *Current Protocols in Molecular Biology*, Greene Publishing Assoc. and Wiley Interscience (1987).

For expression in a suitable host organism, the recombinant nucleic acid construct or gene construct is advantageously inserted into a host-specific vector which allows optimal gene expression in the host. Vectors are well known to the skilled worker and can be found, for example, in "Cloning Vectors" (Pouwels P. H. et al., Ed., Elsevier, Amsterdam-New York-Oxford, 1985). Vectors are to be understood as meaning not only plasmids, but all other vectors known to the skilled worker such as, for example, phages, viruses such as SV40, CMV, baculovirus and adenovirus, transposons, IS elements, phasmids, cosmids, and linear or circular DNA. These vectors can be replicated autonomously in the host organism or chromosomally.

The vectors according to the invention allow the generation of recombinant microorganisms which can be transformed, for example, with at least one vector according to the invention and which can be employed for producing the mutants. The above-described recombinant constructs according to the invention can advantageously be introduced into a suitable host system and expressed. It is preferred to use usual cloning and transfection methods known to the skilled worker, for example coprecipitation, protoplast fusion, electroporation, retroviral transfection and the like, in order to bring about expression of the abovementioned nucleic acids in the expression system in question. Suitable systems are described, for example, in *Current Protocols in Molecular Biology*, F. Ausubel et al., Ed., Wiley Interscience, New York 1997.

Suitable host organisms are, in principle, all organisms which allow expression of the nucleic acids according to the invention, their allelic variants, and their functional equivalents or derivatives. Host organisms are to be understood as meaning, for example, bacteria, fungi, yeasts or plant or animal cells. Preferred organisms are bacteria such as those of the genera

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Escherichia such as, for example, Escherichia coli, Streptomyces, Bacillus or Pseudomonas, eukaryotic microorganisms such as Saccharomyces cerevisiae, Aspergillus, and higher eukaryotic cells from animals or plants, for example Sf9 or CHO cells.

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If desired, expression of the gene product may also be brought about in transgenic organisms such as transgenic animals such as, in particular, mice, sheep, or transgenic plants. The transgenic organisms may also be knock-out animals or plants in which the
10 corresponding endogenous gene has been eliminated, such as, for example, by mutation or partial or complete deletion.

Successfully transformed organisms may be selected by means of marker genes which are also contained in the vector or in the
15 expression cassette. Examples of such marker genes are genes for resistance to antibiotics and genes for enzymes which catalyze a color reaction causing the transformed cell to be colored. They may then be selected by means of automatic cell sorting. Microorganisms which have been transformed successfully with a
20 vector and which carry a suitable gene for resistance to antibiotics (for example G418 or hygromycin) may be selected by suitable liquid or solid media containing antibiotics. Marker proteins presented on the cell surface may be exploited for selection by means of affinity chromatography.

25

The combination of the host organisms and the vectors which match the organisms, such as plasmids, viruses or phages, for example plasmids with the RNA polymerase/promoter system, the phages λ , μ or other temperate phages or transposons and/or further
30 advantageous regulatory sequences, forms an expression system. The term "expression system" is to be understood as meaning, for example, the combination of mammalian cells, such as CHO cells, and vectors, such as pcDNA3neo vector, which are suitable for mammalian cells.

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As described above, the gene product may advantageously also be expressed in transgenic animals, for example mice, sheep, or transgenic plants. Equally, it is possible to program cell-free
40 translation systems with the RNA derived from the nucleic acid.

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The invention relates furthermore to processes for the preparation of a monooxygenase according to the invention, in which a monooxygenase-producing microorganism is cultured, monooxygenase expression is induced, if appropriate, and the
45 monooxygenase is isolated from the culture. In this manner, the

monooxygenase according to the invention may also be produced on an industrial scale, if this is desired.

The microorganism can be cultured and fermented by known methods. 5 Bacteria, for example, can be multiplied in TB or LB medium at a temperature of 20 to 40°C and a pH of 6 to 9. Suitable culture conditions are described in detail for example by T. Maniatis, E.F. Fritsch and J. Sambrook, Molecular Cloning: A Laboratory Manual, Cold Spring Harbor Laboratory, Cold Spring Harbor, NY 10 (1989).

Unless the monooxygenase is secreted into the culture medium, the cells are then interrupted, and the monooxygenase is obtained from the lysate by known protein isolation methods. The cells may 15 be disrupted as desired by high-frequency ultrasound, by high pressure, such as, for example, in a French pressure cell, by osmolysis, by the action of detergents, lytic enzymes or organic solvents, by homogenizers, or by combining a plurality of the methods listed.

20 The monooxygenase may be purified by known methods of chromatography, such as molecular sieve chromatography (gel filtration), such as chromatography on Q-Sepharose, ion-exchange chromatography and hydrophobic chromatography, and by other 25 customary methods such as ultrafiltration, crystallization, salting out, dialysis and native gel electrophoresis. Suitable methods are described, for example, by Cooper, F.G., Biochemische Arbeitsmethoden [Methods in Biochemistry], Verlag Walter de Gruyter, Berlin, New York or by Scopes, R., Protein Purification, 30 Springer Verlag, New York, Heidelberg, Berlin.

To isolate the recombinant protein, it is especially advantageous to use vector systems or oligonucleotides which extend the cDNA by certain nucleotide sequences and thus encode altered 35 polypeptides or fusion proteins for the purposes of simpler purification. Such modifications which are suitable are, for example, tags which act as anchors, for example the modification known as hexa-histidine anchor or epitopes which can be recognized as antigens of antibodies (described, for example, by 40 Harlow, E. and Lane, D., 1988, Antibodies: A Laboratory Manual. Cold Spring Harbor (N.Y.) Press). These anchors can serve to attach the proteins to a solid support such as, for example, a polymer matrix, which may be filled into a chromatography column or used on a microtiter plate or on any other carrier, for 45 example.

10

At the same time, these anchors may also be used for recognizing the proteins. To recognize the proteins, it is additionally possible to use conventional labels, such as fluorescent dyes, enzyme labels which, after reaction with a substrate, form a
5 detectable reaction product, or radiolabels, alone or in combination with the anchors for derivatizing the proteins.

The invention furthermore relates to biochemical processes for the enzymatic production of terminally or subterminally (ω -1 to
10 ω -4) hydroxylated aliphatic carboxylic acids, which comprise

- a1) aerobically culturing a recombinant microorganism according to the invention in the presence of a culture medium which contains at least one hydroxylatable carboxylic acid or at
15 least one hydroxylatable carboxylic acid derivative; or
- a2) aerobically incubating a reaction medium containing at least one hydroxylatable carboxylic acid or at least one
20 hydroxylatable carboxylic acid derivative with a mutant according to the invention, and
- b) isolating the resulting hydroxylated product or product mixture from the medium.

25 The carboxylic acids can be employed in the process according to the invention per se or as derivatives thereof, such as, in particular, C_1 - C_4 -alkyl esters or carboxamides.

Hydroxylatable carboxylic acids which are preferably employed in
30 the process according to the invention are C_8 - C_{30} -monocarboxylic acids or derivatives thereof.

A hydroxylatable carboxylic acid which is especially preferably used in the process according to the invention is a
35 C_8 - C_{12} -monocarboxylic acid or a derivative thereof, and a monooxygenase which is especially preferably used in the process according to the invention is a mutant in accordance with the above group (A).

40 In accordance with another process according to the invention, the hydroxylatable carboxylic acid used is a
 C_{12} - C_{30} -monocarboxylic acid or a derivative thereof and the monooxygenase is a mutant selected from amongst the single mutants F87A, F87V, V26T, S72G, A74G and M354T, and the multiple
45 mutants f) to i) in accordance with the above group (A).

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The oxidation reaction according to the invention is usually carried out in the presence of atmospheric oxygen and in the presence of an electron donor (or reduction equivalent) such as, in particular, NADH, NADPH and Zn/Co(III) sepulchrates. The use of Zn/Co(III) sepulchrates is described, for example, in DE-A-199 35 115 which is herewith expressly referred to.

If the hydroxylation according to the invention is carried out with a recombinant microorganism, it is preferred first to culture the microorganisms in the presence of oxygen and in a complex medium such as, for example, TB or LB medium, at a cultivation temperature of approximately 20 to 40°C and a pH of approximately 6 to 9 until a sufficient cell density is reached. Exogenous substrate is added as required. In order better to control the oxidation reaction, the use of an inducible, in particular a temperature-inducible, promoter is preferred. Here, the temperature is raised to the induction temperature required, for example 42°C in the case of the P_{rP_1} promoter, maintained over a sufficient period, for example 1 to 10 or 5 to 6 hours, to express the monooxygenase activity, and the temperature is then dropped to a value of approximately 30 to 40°C. Culturing is then continued for 12 hours to 3 days in the presence of oxygen.

If, in contrast, the oxidation according to the invention is carried out with purified or concentrated enzyme, the enzyme mutant according to the invention is dissolved in a medium comprising exogenous substrate (approximately 0.01 to 10 mM, or 0.05 to 5 mM), and the reaction is carried out, preferably in the presence of oxygen, at a temperature of approximately 10 to 50°C, such as, for example, 30 to 40°C, and a pH of approximately 6 to 9 (such as, for example, adjusted with 100 to 200 mM phosphate or Tris buffer), and in the presence of a reducing agent, during which process the substrate-comprising medium furthermore may exhibit an approximately 1 to 100-fold molar excess of reduction equivalents, based on the substrate to be oxidized. If required, the reducing agent may be added portionwise.

If required, oxygen may be passed into the reaction medium in a manner known per se.

40

If the processes according to the invention are carried out with enriched or purified enzyme, for example the following reaction conditions may be set:

45 Substrate concentration:	0.1 to 20 mg/ml
Enzyme concentration:	0.1 to 10 mg/ml
Reaction temperature:	20 to 40°C

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pH: 6 to 8
Buffer: 0.05 to 0.2 M potassium
phosphate, Tris/HCl
Electron donor: is preferably added portionwise
5 (initial concentration
approx. 0.1 to 2 mg/ml).

Before the reaction is started by adding the electron donor, it
is possible to increase the activity by adding acetone in a
10 concentration of 1 to 5% (v/v) and briefly preincubating (1 to 5
minutes at approximately 20 to 40°C).

The skilled worker may deviate from these conditions and optimize
the reaction conditions in question by routine experiments.

15

Two different strategies exist in protein engineering for
generating variants with modified enzymatic properties: firstly,
the "rational design" method (4), and secondly, the "directed
evolution" method (5-7). Of central importance for successful
20 rational design are a highly resolved three-dimensional
structural model and an in-depth knowledge of the enzyme
mechanism. While the rational design has been shown to generate
enzyme mutants which have a high activity for unnatural
substrates (4), the effect of individual amino acid point
25 substitutions on stability, activity and specificity of the
mutants can frequently not be predicted.

Even through X-ray structures of P450 BM-3 have been deposited in
the protein database (8), the conformation of substrate and P450
30 during the critical hydroxylation stage remains unclear (9-11).
Of central importance for the directed-evolution method is an
efficient detection method for the rapid screening of large
libraries of random mutants. An optical test for the P450 BM-3
mutant F87A, which employs ω -para-nitrophenoxycarboxylic acids
35 (pNCA), has proved to be useful (12, 13). The single mutant F87A
shifts the hydroxylation position of fatty acids from position
 ω -1, ω -2 and ω -3 towards the ω -position (13) and additionally
leads to a complete conversion of 12-pNCA compared with a 33%
conversion observed for the wild-type enzyme (12). However, since
40 the monooxygenase domain of P450 BM-3 encompasses over 400 amino
acids, the screening of a random-mutant library is like looking
for a needle in a haystack.

To improve the efficiency of the searching procedure, the
45 rational-design method was combined in accordance with the
directed-evolution method so as to generate mutants with a
modified reactivity, in particular for generating mutants with

13

the specificity for fatty acids with medium chain length. The "rational evolution" method according to the invention is based on a computer-aided protein modeling to generate a virtual random library and to identify residues which are highly likely to
5 affect the desired properties. A sublibrary is generated by randomizing these residues and screened for positive mutants. Starting from a structural model, the first step is the determination of residues which are potentially important for chain-length specificity. To generate mutants with improved
10 properties, the mutation site proposed by the model is modified with the aid of the saturation mutagens. Then, the individual mutants with the best properties are combined with each other taking into consideration the rational design. The application of this combined strategy made it possible in particular to improve
15 the activity of P450 BM-3 for substrates of medium chain length.

The application of this strategy and the sequence homology to P450 enzymes of different origins allow the skilled worker analogously to generate other mutants which are also the subject
20 of the invention.

The present invention will now be illustrated by the following experiment description and taking into consideration the appended figures. The figures show:

25

Figure 1: the stepwise optimization of P450 BM-3 for the new substrate 8-pNCA. The catalytic efficiency over 8-pNCA is shown for each mutant (in the unit $s^{-1}M^{-1}$); and

30 Figure 2: a model of the complex of the P450 BM-3-mutant LARVF with the substrate 8-pNCA. The side chains which show the five best positions for mutations and which were combined to give the mutant LARVF are shown (V26T, R47F, A74G, F87V, L188K).

35 Method 1: Modeling the substrate/P450 BM-3 complex

The modeling of the substrate/enzyme complex was based on the structure of P450 BM-3 which had been determined by crystallography, complexed with palmitoleic acid (9). This
40 structure is deposited at the protein database (8). The crystal structure described, at a resolution of 2.9 Å, contains four molecules in an asymmetric unit cell. Chain A was selected as reference for the modeled complex. A model of 8-pNCA was generated as substrate molecule using the SYBYL "Molecule
45 Builder" (Tripos, Inc., St. Louis, USA). The F87A mutation was generated using the SYBYL Biopolymer Tool. The carbon atoms 1 to 4 of the substrate were placed into the binding site matching the

14

carbon atoms 6 to 9 of the bound palmitoleic acid. The torsion angle of the fatty acid chain was chosen in accordance with the transconfiguration step. NMR studies on P450 BM-3/laurate complexes and P450 BM-3/12-bromolaurate complexes demonstrated
 5 that the protons of the hydroxylated carbon atoms (C10 and C11) are at an approximate distance of 3.0 Å from the heme iron, which is in the II oxidation state (10, 13). As a result of this finding, the corresponding atoms C7 and C8 of 8-pNCA were placed at a distance of 4 Å and 3.6 Å, respectively, from the heme iron.
 10 The para-nitrophenoxy group was arranged manually in the binding pocket. Also, the energy of the complex was minimized by fixed backbone atoms.

Method 2: Saturation mutagenesis

15

The mutants used in accordance with the invention were generated with the aid of saturation mutagenesis using the Stratagene QuikChange Kit (La Jolla, California, USA). Nine positions in the vicinity of the substrate binding channel, viz. P25, V26, R47,
 20 Y51, S72, A74, F87, L188 and M354, were selected for mutation via P450 BM-3 modeling. The primers for each of these positions are compiled in Table 1.

Table 1:

25	Selected positions	Primers	Sequence No.
30	P25	5'-gttattaaacacagataaannngttcaagctttgatg-3' 5'-catcaaagcttgaacnnntttatctgtgtttaataac-3'	SEQ ID NO: 9 SEQ ID NO: 10
	V26	5'-gttattaaacacagataaaccgnnncaagctttgatg-3' 5'-catcaaagcttgnnncggtttatctgtgtttaataac-3'	SEQ ID NO: 11 SEQ ID NO: 12
35	R47	5'-cgaggcgcctggtnnngtaacgcgctacttacc-3' 5'-gataagtagcgcgttacnnnaccaggcgcctcg-3'	SEQ ID NO: 13 SEQ ID NO: 14
	Y51	5'-cctggtcgtgtaacgcgcnnnttatcaagtcagc-3' 5'-gctgacttgataannngcgcgttacacgaccagg-3'	SEQ ID NO: 15 SEQ ID NO: 16
40	S72	5'-gctttgataaaaacttannncaagcgcttaaatttgtagc-3' 5'-cgtacaaatttaagcgttgnnnntaagtttttatcaaagc-3'	SEQ ID NO: 17 SEQ ID NO: 18
	A74	5'-gctttgataaaaacttaaaagtcaannncttaaatttgtagc-3' 5'-cgtacaaatttaagnnnnttgacttaagtttttatcaaagc-3'	SEQ ID NO: 7 SEQ ID NO: 8

15

5	L188	5'-gaagcaatgaacaagnnncagcgagcaaatccag-3'	SEQ ID NO: 5
		5'-ctggatttgctcgctggnncttggttcattgcttc-3'	SEQ ID NO: 6
	M354	5'-ggcgacgaactannngttctgattcctcag-3'	SEQ ID NO: 19
		5'-ctgaggaatcagaacnnntagttcgctgcc-3'	SEQ ID NO: 20
	F87	5'-gcaggagacggggttgnnnacaagctggacg-3'	SEQ ID NO: 3
		5'-cgtccagcttgtnnncaaccccgctctcctgc-3'	SEQ ID NO: 4

10

The reaction conditions were identical for all mutagenic PCR processes, with the exception of the annealing temperature, which was varied as follows: 50°C for positions 25, 26, 188 and 354; 52°C for positions 47 and 51; and 46°C for positions 72, 74 and 87. The reactions were carried out in reaction volumes of 50 µl, each batch containing 17.5 pmol of each primer, 20 pmol of the template plasmid DNA, 3 U of the Pfu polymerase and 3.25 nmol of each dNTP. The reaction was started at 95°C, 4 minutes, and the batch then undergoes the following thermocycle 20 times: 95°C, 1 minute; 46-52°C, 2.5 minutes; 72°C, 17 minutes; after these 20 cycles, the reaction was continued for 15 minutes at 72°C. To carry out a site-specific mutagenesis by PCR, an individual codon was altered for exchanging one amino acid. To randomize a specific amino acid, primers were used in which "nnn" encodes the specific amino acid. All PCR product solutions were treated for 3 hours at 37°C with 20 U DpnI to digest the original unmutated template DNA. Transformation into E. coli DH5α was then carried out.

30 Method 3: Expression and purification of wild-type enzyme and of the mutants

The P450 BM-3 wild-type gene and its mutants were expressed under the control of the strong temperature-inducible P_{RPL} promoter pCYTEXPl into E. coli strain DH5α (supE44, lacU169 [80lacZ M15] hsdR17 recA1 endA1 gyrA96 thi-1 relA1). The single point mutation F87A was introduced in accordance with the prior art (12). The transformed cells were plated onto LB agar plates which contained 100 µg/ml ampicillin. After the colonies had grown for 12 to 24 hours, they were picked up with sterile toothpicks and placed into 96-well microtiter plates, each well containing 200 µl of TB medium (12 g tryptophan, 24 g yeast extract, 4 ml glycerol, (distilled) H₂O to 1 liter) together with 100 µg/ml ampicillin. The plates were incubated overnight at 37°C. 40 µl were subsequently removed from each well and transferred into culture tubes which contained 2 ml TB medium with 100 µg/ml ampicillin, and the batches were subsequently incubated for 2 hours at 37°C

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and then for 6 hours at 42°C. The cells were removed by centrifugation for 5 minutes at 4000 rpm, treated with chicken albumen lysozyme (1 U/ml), and then twice frozen and defrosted. The crude cell extracts were obtained by centrifugation for 5 10 minutes at 14,000 rpm. The activity was measured in the resulting supernatant. To produce large quantities of enzyme, a 2-l shake flask with 300 ml of TB medium with 100 µg/ml ampicillin was used, incubated at 37°C, shaken for 2 hours at 200 rpm ($OD_{578nm} = 0.8$ to 1.0) and subsequently incubated for 10 6 hours at 42°C. The cells were collected by centrifugation for 10 minutes at 4000 rpm and suspended in 15 ml of 0.1 M potassium phosphate buffer, pH 7.4. The ice-cooled suspension was disrupted with the aid of a Branson sonifier W25 (Dietzenbach, Germany) (80 W, 2 minutes, 3 cycles). The suspension was centrifuged for 15 20 minutes at 32570 x g. The crude extracts were used for determining the enzyme activity or for enzyme purification.

Enzyme purification was carried out as described in (14), but using a BioPilot chromatography (Pharmacia, Sweden). Enzyme 20 purity was determined by determining the total protein and the amount of enzyme. The concentration of purified enzyme was determined from the difference between the absorption spectrum of the carbonyl complex of the iron(II) form in comparison with the iron(II) form using a molecular absorptivity of 91 mM⁻¹ cm⁻¹ for 25 the wavelength pair 450 nm and 490 nm (1).

Method 4: Isolation of mutants with higher activity for substrates of shorter chain length

30 Instead of the wild type, the P450 BM-3 mutant F87A was used as template DNA. The mutations for the position in question were generated as described above. In each case approximately 100 colonies were picked for screening the sequence zone at each position and grown in culture tubes, and cells were isolated 35 therefrom and lysed. The crude cell extracts from each selected colony were used for the activity test. All mutants which showed a higher activity than F87A for at least one substrate with a shorter chain length than 15-pNCA was sequenced for identifying the mutations.

40

The mutant with the highest activity for 12-pNCA, 10-pNCA or 8-pNCA, respectively, amongst all mutants for the same position was selected for a later combination with other mutations. The combined mutation was carried out stepwise by site-specific 45 mutagenesis. The combinatory procedure is shown in Figure 1. Six colonies were isolated from each combination step to determine the substrate specificity. A colony with a representative

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substrate specificity was selected, and the substrate specificity was determined for the pure enzyme. The plasmid of the selected colony was used for the next step of the site-specific mutagenesis. The mutations in the final mutant were identified by 5 DNA sequencing (ABI PRISM[®] BigDye[™] Terminator Cycle Sequencing Ready Reaction Kit and ABI Prism[™] 377 DNA Sequencer).

Method 5: Enzyme activity assay

10 For the pNCA activity assay use was made of 8 µl of a 10 mM pNCA solution in DMSO in a disposable cell in an end volume of 1 ml. After 850 µl of Tris/HCl buffer (0.1 M, pH 8.2) and 0.1 to 0.4 nmol P450 had been added to the pNCA/DMSO solution in question, the samples were preincubated for 5 minutes before the 15 reaction was started by adding 50 µl of an aqueous solution of 1 mM NADPH. To determine K_{cat} and K_m, a concentration series was established for the various pNCA substrates (regarding details of the detection method, see (12)).

20 A 96-well plate (Greiner, Frickenhausen, Germany) was used for carrying out the pNCA test in a microtiter plate. In a total reaction volume of 250 µl in Tris/HCl buffer (0.1 M, pH 8.2), the reaction batch contained either 60 nmol 8-pNCA, 15 nmol 10-pNCA, 15 nmol 12-pNCA or 15 nmol 15-pNCA, in each case dissolved in 25 2.5 µl of DMSO. After the samples had been preincubated for 5 minutes with 40 µl of P450 BM-3 samples, the reaction was started by injecting, into each well, 30 µl of a 1 mM NADPH solution. Immediately after the NADPH solution had been added, the plates were measured in a plate reader at 405 nm.

30

Method 6: Conversion of carboxylic acids using mutants according to the invention, and identification of the products

a) Chemical reaction

35

The following batch was chosen to hydroxylate the fatty acids in the presence of P450 BM-3 or its mutants:

P450 BM-3 mutant	20 mg	
40 Reaction buffer	20 ml	(Tris/HCl 50mM, KCl 250mM, pH 7.8)
Fatty acid	10 mg	
Acetone	400 µl	(2 % v/v) (accelerates the reaction by a factor of 2)

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Prior to the reaction, the enzyme lyophilisate was dissolved in 1 ml of reaction buffer and first incubated for 30 minutes at 36°C. Like the addition of 2% v/v acetone, the incubation leads to an increase in activity of 60 and 75%, respectively.

5

After 5 minutes' incubation, 500 µl of the previously prepared NADPH solution (12.5 mg/ml) were added. The course of the reaction is monitored by absorption measurements at 340 nm, and the consumption of NADPH can be observed. Theoretically 4 ml of NADPH solution would be required for a stoichiometric conversion, however, an unduly high NADPH concentration in the reaction solution results in inactivation of the enzyme, which is why the cofactor is added in 500 µl steps.

15 After the reaction had ended, the solution was acidified with 5M hydrochloric acid to a pH of 2. The fatty acids or hydroxylated fatty acids precipitate during this and result in a noticeable cloudiness of the solution. Thereafter, the mixture was extracted twice with in each case 10 ml of dichloromethane and dried over sodium sulfate. After filtration through a folded filter, the dichloromethane was removed on a rotary evaporator or by evaporation with nitrogen. The white solid which remained was taken up in 2 ml of dichloromethane and used in the GC analysis.

25 b) Analysis by gas chromatography

A Fisons gas chromatograph (Fisons Instruments Mega Series, Mainz, Germany) equipped with FID was used for the analysis (Optima 5-column, internal diameter 25 m x 0.25 mm, Macherey & Nagel, Düren, Germany).

For analysis, starting materials and products were silylated with MSHFBA. During this, all hydroxyl and acid groups are converted into the corresponding trimethylsilyl ethers and esters, respectively. Care must be taken that the sample is anhydrous since otherwise side reactions with the silylating agent result. 15 µl of MSHFBA were pipetted into 10 µl of the hydroxy-fatty-acid-containing dichloromethane solution and the mixture was incubated for 15 minutes at room temperature. After 25 µl of dichloromethane had been added, the GC analysis was carried out.

To this end, 1 µl of the silylated samples were injected into the gas chromatograph. Injector and detector temperature were 350°C. The following temperature programmes were used:

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Caprylic acid

100 °C (2 min) $\xrightarrow{5^\circ/\text{min}}$ 200 °C $\xrightarrow{10^\circ/\text{min}}$ 300 °C (5 min)

5 Capric acid

100 °C (2 min) $\xrightarrow{5^\circ/\text{min}}$ 140 °C (5 min) $\xrightarrow{10^\circ/\text{min}}$ 300 °C (5 min)

Lauric acid

10 100 °C (2 min) $\xrightarrow{5^\circ/\text{min}}$ 170 °C (5 min) $\xrightarrow{10^\circ/\text{min}}$ 300 °C (5 min)Example 1: Selection of the starting mutant

- 15 The P450 BM-3 single mutant F87A was used as starting template. As already mentioned, this mutation shifts the hydroxylation position in saturated C12- and C14-fatty acids of ω -1, ω -2 and ω -3 towards the ω -position (13). For the conversion of 12-pNCA and 15-pNCA, it was also shown that the ω -hydroxylation is
- 20 enhanced significantly over the wild type (12). As regards the ω -hydroxylation of 12-pNCA, a complete conversion was obtained compared with a 33% conversion in the case of the wild type. In addition to the increased regioselectivity, increased activities for 12-pNCA and 15-pNCA were also observed (compare Table 2).

- 25 Table 2: Specific activity of selected P450 BM-3 mutants for various pNCA derivatives with different chain lengths¹

30 Substrate	WT	F87A	L188K	V26T	R47F	S72G	A74G	M354T
15-pNCA	405	410	288	519	258	439	474	560
12-pNCA	141	284	316	555	233	596	517	480
10-pNCA	339	92	207	106	52	150	103	171
8-pNCA	15	2	69	16	13	3	6	4

- 35 ¹ Units of specific activity: nmol/min/nmol P450

The increased regioselectivity of F87A can be understood with reference to the structural model. The substitution of the bulky residue F87 by alanine enlarges the binding pocket for the

40 p-nitrophenoxy group formed by F87, and also by V78, A82, T260, I263 and A264. In addition, the access of the large p-nitrophenoxy group to the binding pocket is facilitated and the steric interactions between F87 and the carbon atoms ω -2 and ω -1 of the pNCA are eliminated. This allows a more advantageous

45 orientation of the ω -position relative to the heme iron atom.

20

Example 2: Selection of individual mutation positions by modeling, site-specific randomization mutagenesis of selected positions, and screening

5 1. Selection of the mutation positions

The model of the bound C8-pNCA substrate shows that the carboxylate is at a distance of 9 and 11 Å from the carboxylate-binding residues R47 and Y51, respectively. To induce activity for C8 substrates, it is necessary to generate a new binding site which is at a suitable distance from the carboxylate group of the substrate. Additional residues should be positioned within the binding site to facilitate the binding of 8-pNCA. The following residues were selected: the residues R47 and Y51, which form the original carboxylate binding site. For R47, it is proposed to form an ion pair between its guanidinium group and the carboxylate residue of the substrate; Y51 forms a hydrogen bridge with the carboxylate group of the substrate (9). In the palmitoleic acid/P450 BM-3 complex, the distance between the C_α atom of R47 and the C atom of the fatty acid carboxylate group is 12 Å. All residues in the hemisphere with a 12 Å radius around the carboxylate group of the 8-pNCA model were identified, and only those were selected within the binding pocket which have side chains pointing towards the carboxylate group of the fatty acid. In this manner, P25, V26, S72, A74, L188 and M354 were selected, and these are probably capable of forming a new carboxylate binding site for short-chain pNCA compounds. These six selected residues are located on secondary structural elements with a flexible conformation (11).

30

2. Mutation and screening

Mutants of each of the eight selected residues were generated by site-specific randomization of the wild-type codon at the positions in question. To ensure that most of the 19 possible amino acid species are tested, 100 colonies of each position were isolated, cultured and tested for activity (the probability that each amino acid is tested is thus greater than 95%, with the exception of a probability of 79% for tryptophan and methionin). The mutants with a higher activity value for at least one substrate with a shorter chain length than 15-pNCA were selected for sequencing for identifying the mutation(s).

It emerged that position 188 is relatively variable. Most of the 100 colonies showed activity for pNCA. From these, 37 colonies were selected in accordance with their activity for 8-pNCA. 16 different amino acid types inclusive of the wild type were

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- detected. This result furthermore confirmed that the selection of 100 colonies was sufficient to ensure that most of the 20 amino acids which are possible can be tested. Amongst the 15 substitutions, substitutions K, R, W, Q, N, G, A and S
- 5 significantly increased the catalytic activity for substrates of shorter chain lengths. The substitution of L by negatively charged amino acids led to an activity for 10-pNCA, 12-pNCA and 15-pNCA which was reduced by a factor of three to seven.
- 10 The remaining seven positions were randomized in a manner similar to position 188. 7 to 19 colonies were selected from each position for DNA sequencing for detecting the mutation(s). Most of these genes were either unmutated, or else the gene product showed reduced activity for substrates of shorter chain lengths
- 15 (the tests were carried out with pure enzyme). In each case only one mutant of positions 26, 47, 74 and 354, two mutants of position 72 and no mutants of positions P25 and Y51 showed a higher activity for substrates of shorter chain length in comparison with 15-pNCA. The mutant with the highest activity for
- 20 8-pNCA in position 188 and position 72, and also single mutants of positions 26, 47, 74 and 354 were selected for a combination. These mutations, which are listed in the above Table 2, contain the following substitutions: V26T, R47F, S72G, A74G, L188K and M354T. In comparison with F87A, the specific activity for 8-pNCA
- 25 was increased by the factor 0.5 to 33.5. Each of these mutations was combined stepwise with the original mutation F87A.

Example 3: Multiple mutants generated by stepwise combination of mutants, and their screening

30

1. Mutant L (F87A, L188K)

- The selection of the first mutant is critical since the combination of single mutants does not necessarily result in a
- 35 cumulation of the individual effects. The wrong selection of the first mutation might lead towards an evolutionary pathway which does not result in an optimal multiple mutation. In the case of a large starting pool of single mutants, an enormous combinatory diversity is likely and, as a consequence, finding the desired
- 40 multiple mutant is unlikely.

- Two criteria favor the selection of mutant L as starting material: its increased activity for 8-pNCA compared with all other mutants (Table 2), and the changes in the enzyme/substrate
- 45 interaction and the properties of the binding site. To verify these changes, structural models of the selected mutants were generated by replacing the side chains of the mutation positions

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with the aid of the SYBYL method. L188 is located on the C terminus of the α -helix F. This helix and the vicinal G helices experience the greatest shift by substrate binding (9). The model illustrates that the exchange of leucine for lysine leads to the formation of a novel putative carboxylate binding site. The distance between the amino group of K188 with the carboxylate residue of 8-pNCA is 6 Å and thus comparable with the distance of the carboxylate group of palmitoleic acid and of the guanidinium group from R47 (the original binding residue), which value has been determined experimentally. The distance between the guanidinium group of R47 and the carboxylate group of 8-pNCA is 11.4 Å. It can therefore be proposed that the ion-pair reactions between the carboxylate group of the substrate and K188 together with the hydroxylated C8 atom take place in a reactive distance to the heme iron atom.

The other five mutants were combined stepwise with mutant L by site-specific mutagenesis (compare Figure 1). A structural model of the mutants selected was generated for each mutagenesis step. The effects, of the mutants generated, on substrate binding was studied with reference to this model, and, on this basis, a rational explanation for the optimized properties of the mutants and their combinations was proposed.

25 2. Mutant LA (F87A, L188K, A74G)

Catalytic efficiency over 8-pNCA was increased by introducing mutation A74G into mutant L. A74 is located on the N-terminus of the α -helix B'. Since the side chain of A74 sterically interacts with the amino group of K188, this interaction is eliminated by exchanging A74 for glycine, thus allowing a more advantageous orientation of the side chain relative to the carboxylate group of the substrate.

35 3. Mutant LAR (F87A, L188K, A74G, R47F)

The catalytic efficiency for 8-pNCA was successfully improved by introducing the additional mutation R47F. The mutation R47F had two possible effects. Phenylalanine hinders the original carboxylate binding and enlarges the hydrophobic section, which is exposed to the solvent, at the entrance of the binding channel formed by the residues F11, L14, L17, P18, P45 and A191 (compare Figure 2). This hydrophobic section is particularly important for attaching the substrate (11).

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4. Mutant LARV (F87A, L188K, A74G, R47F, V26T)

If the mutation M354T is added to mutant LAR, the Kcat value for 8-pCNA is reduced. M354T was therefore not involved in further combination experiments. However, if the mutation V26T is added to mutant LAR, the resulting mutant LARV shows a slightly higher Kcat value and a slightly lower Km value than LAR. The catalytic efficiency for 8-pNCA was increased. If, instead, mutation S72G is carried out in mutant LAR, the Kcat value of 8-pNCA was reduced. This is why mutant LARV was selected for further mutations.

V26 is located at the N-terminus of the α -helix A. The model suggests that T26 might assume the role of the original residue Y51 of the binding site and might stabilize the carboxylate group of the substrate by forming a hydrogen bridge. The distance between the hydroxyl group of T26 and the amino group of K188 is 6.9 Å. Compared with the original binding site, this distance is approximately 2 Å greater (4.8 Å between the hydroxyl group of Y51 and the guanidinium group of R47). It is therefore possible that the K188-containing F helix is subjected to further conformational alterations, owing to which 8-pNCA is retained deeper down in the binding region, and the distance between T26 and K188 is reduced.

25

5. Mutant LARVF (F87V, L188K, A74G, R47F, V26T)

It was possible to demonstrate that position 87 is of particular importance for the catalytic activity and the substrate specificity of the enzyme (3, 13). This is why mutant LARV was optimized in position 87 by site-specific randomized mutagenesis. Amongst 100 colonies, one mutant was obtained which exhibited a catalytic efficiency of $3.5 \times 10^4 \text{ s}^{-1} \text{ M}^{-1}$ for 8-pNCA. The DNA sequence data revealed that alanine in position 87 was replaced by valine.

It is known from the crystal structure (11) and earlier experiments (3, 13) that R87 is important for the access of the substrate to the heme iron. The bulky para-nitrophenyl group of this substance made it necessary to increase the size of the binding site by exchanging phenylalanine for alanine. By exchanging A87 for valine, the contact of C_o with the heme iron atom is improved, owing to steric interactions between the ether oxygen and the V87 side chain.

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The data reveal that two key steps, F87A to L and LARV to LARVF, increased the catalytic efficiency for 8-pNCA. This raised the question as to whether the other mutations in mutant LARVF can be reversed without losing the activity for 8-pNCA. Mutants were therefore generated which contain mutation F87V instead of mutation F87A. These mutants have the following names:

- 1.) L7V with the mutations F87V L188K
- 2.) AL7V with the mutations F87V L188K A74G
- 10 3.) ARL7V with the mutations F87V L188K A74G R47F

The following results were obtained in the activity assays.

Table 3: Kinetic parameters of P450 BM-3 mutants for pNCA derivatives of different chain lengths, determined at pH 8.0 and 25°C

	Kcat (s ⁻¹)			Km (μM)			Kcat/Km (s ⁻¹ M ⁻¹)		
	12	10	8	12	10	8	12	10	8
20 F87V	0.7	1.8	-	3.8	8.5	-	1.7·10 ⁵	2.1·10 ⁵	-
L7V	2.8	4.7	-	6.4	14.2	-	4.3·10 ⁵	3.3·10 ⁵	-
AL7V	2.2	5.9	4.3	15.1	22.7	197.6	1.4·10 ⁵	2.6·10 ⁵	2.0·10 ⁴
ARL7V	1.4	5.5	3.9	8.9	17.5	41.4	1.7·10 ⁵	3.1·10 ⁵	9.3·10 ⁴
25 ARVLF	1.4	7.2	0.2	12.3	44.8	6.5	9.2·10 ⁴	1.6·10 ⁵	3.5·10 ⁴

The results show that mutant F87V and L7V show no measurable conversion for the substrate 8-pNCA. The results furthermore show that the quadruple mutant ARL7V shows an even better catalytic efficiency than the quintuple mutant ARVLF.

30

Moreover, mutants ARL7V and ARVLF show high activities for capric acid (C10), which is shorter by two carbon atoms than the shortest native fatty acid substrate of the wild-type enzyme. Moreover, ω-4-monohydroxylated products were observed when lauric acid (C12) is used as substrate, while the wild-type enzyme of P450 BM-3 is only active in the positions ω-1, ω-2 and ω-3.

Example 4: Determination of the preferred hydroxylation position for carboxylic acids of different chain lengths and various mutants, and comparison with the wild-type enzyme

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The reaction batches are worked up and analyzed in accordance with the above-described method (6).

45

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The results are compiled in Table 4 below.

Table 4:

5	Hydroxylation positions	Capric acid (C10)	Lauric acid (C12)
		[%]	[%]
	Wild type		
	ω -3	-	34
10	ω -2	-	28
	ω -1	-	38
	Mutant L7V		
	ω -3	-	53
15	ω -2	-	30
	ω -1	-	17
	Mutant F87V		
	ω -3	-	51
20	ω -2	-	25
	ω -1	-	24
	Mutant AL7V		
	ω -3	-	28
	ω -2	-	54
25	ω -1	-	18
	Mutant ARL7V		
	ω -3	14	35
	ω -2	33	50
30	ω -1	53	15
	Mutant ARVLF		
	ω -3	15	34
	ω -2	30	53
35	ω -1	55	13

What is noticeable in the hydroxylation of lauric acid is that a change in regioselectivity first takes place during the transition from the wild type to P450 BM-3 F87V, which preferentially catalyzes an ω -3 hydroxylation, as is the case with P450 BM-3 L7V. During the transition to the triple mutant, the regioselectivity changes again; P450 BM-3 AL7V, P450 BM-3 ARL7V and P450 BM-3 ARVLF preferentially direct the hydroxylation to the ω -2 position.

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All GC analyses demonstrate that capric acid is only converted by P450 BM-3 ARVLF and P450 BM-3 ARL7V, while a conversion of less than 1% is found in the other mutants. Both enzymes exhibit a virtually identical regioselectivity, with the ω -1 position being preferred.

To determine the reaction yields, gas chromatograms of standards were recorded. The starting material standard used was capric or lauric acid solution with dichloromethane as solvent (concentration 0.5 mg/ml). Owing to the FID detection method, it was not possible to simply compare the peak areas of starting materials and products with one another since molecules which have different structural and empirical formulae generate different ion fluxes upon combustion. These ion fluxes are not proportional to the quantitative ratio of starting material and product. The product standard used was therefore commercially available 10-hydroxycapric acid or 12-lauric acid. The empirical formulae of the standards and of the products are identical, and the structure only differs with regard to the position of the hydroxyl group, which is why approximately identical detectable ion fluxes can be assumed for identical quantities.

In the hydroxylations of capric acid with P450 BM-3 ARVLF and P450 BM-3 ARL7V catalysis, the cumulative product yields were 57% and 38%, respectively. In the hydroxylations of lauric acid, the yield was 51% for P450 BM-3 ARVLF catalysis and between 38% and 40% for all other mutants and for the wild type.

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<210> 19
<211> 30
<212> DNA
<213> Artificial sequence
<220>
<223> Description of the artificial sequence: PCR primer
<400> 19
ggcgacgaac tannngttct gattcctcag 30

<210> 20
<211> 30
<212> DNA
<213> Artificial sequence
<220>

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<223> Description of the artificial sequence: PCR primer

<400> 20

ctgaggaatc agaacnnnta gtctgctgcc

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We claim:

1. A modified cytochrome P450 monooxygenase which, in comparison
5 with the wild-type enzyme, shows an altered substrate profile
in the terminal and/or subterminal enzymatic hydroxylation of
aliphatic carboxylic acids, owing to site-specific
mutagenesis of its substrate binding region.
- 10 2. A monooxygenase as claimed in claim 1, which is derived from
cytochrome P450 monooxygenases of bacterial origin.
3. A monooxygenase as claimed in claim 2, which is derived from
15 *Bacillus megaterium* cytochrome P450 monooxygenase BM-3 with
an amino acid sequence in accordance with SEQ ID NO: 2, which
has at least one functional mutation in one of the following
amino acid sequence regions: 24-28, 45-51, 70-72, 73-82,
86-88, 172-224 und 352-356, with the proviso that, if the
20 enzyme carries the mutation F87A, more than one of these
regions is mutated.
4. A monooxygenase as claimed in claim 3, which comprises at
least one functional mutation in the amino acid sequence
25 regions 86-88 and 172-224.
5. A monooxygenase as claimed in claim 4, which comprises at
least one of the following amino acid substitution patterns:
 - 30 a) F87V;
 - b) F87A L188K;
 - c) F87V L188K;
 - d) F87A L188K A74G;
 - e) F87V L188K A74G;
 - f) F87A L188K A74G R47F;
 - 35 g) F87V L188K A74G R47F;
 - h) F87A L188K A74G R47F V26T; or
 - i) F87V L188K A74G R47F V26T;
- and functional equivalents thereof.
- 40 6. A monooxygenase as claimed in claim 3, which comprises a
single amino acid substitution from amongst the following:
 - 45 a) V26T,
 - b) R47F,
 - c) S72G,
 - d) A74G,

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- e) F87V,
- f) L188z, where Z is an amino acid selected from amongst K, R, W, Q, N, G, A and S, and
- g) M354T;

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and functional equivalents thereof.

- 7. A nucleic acid sequence encoding a monooxygenase as claimed in any of the preceding claims and the complementary nucleic acid sequence thereof.
- 8. An expression construct comprising, under the genetic control of regulatory nucleic acid sequences, an encoding sequence which encompasses a nucleic acid sequence as claimed in claim 7.
- 9. A vector which encompasses at least one expression construct as claimed in claim 8.
- 10. A recombinant microorganism which has been transformed with at least one vector as claimed in claim 9.
- 11. A microorganism as claimed in claim 10, selected from amongst bacteria of the genus Escherichia.
- 12. A process for the enzymatic production of terminally or subterminally hydroxylated aliphatic carboxylic acids, which comprises
 - a1) culturing a recombinant microorganism as claimed in claim 10 or 11 according to the invention in the presence of a culture medium which contains at least one hydroxylatable carboxylic acid or at least one hydroxylatable carboxylic acid derivative; or
 - a2) incubating a reaction medium containing at least one hydroxylatable carboxylic acid or at least one hydroxylatable carboxylic acid derivative with an enzyme as claimed in any of claims 1 to 6, and
 - b) isolating the resulting hydroxylated product from the medium.
- 13. A method as claimed in claim 12, wherein the hydroxylatable carboxylic acid is a C₈-C₃₀ monocarboxylic acid or a derivative thereof.

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14. A method as claimed in claim 13, wherein the hydroxylatable carboxylic acid is a C₈-C₁₂-monocarboxylic acid or a derivative thereof and the monooxygenase used is a mutant as claimed in claim 5.

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15. A method as claimed in claim 13, wherein the hydroxylatable carboxylic acid is a C₁₂-C₃₀-monocarboxylic acid or a derivative thereof and the monooxygenase employed is a mutant selected from amongst the single mutants F87A, F87V, V26T, S72G, A74G and M354T, and the multiple mutants F87A L188K A74G R47F; F87V L188K A74G R47F; F87A L188K A74G R47F V26T; or F87V L188K A74G R47F V26T.

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16. A method as claimed in any of claims 12 to 15, wherein the reaction is carried out in the presence of an electron donor or a reduction equivalent.

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17. A method as claimed in claim 16, wherein the electron donor or the reduction equivalent is selected from amongst NADH, NADPH and Zn/Co(III) sephalchrate.

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Application number/ Numéro de demande : EP00-07252

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Fig. 1

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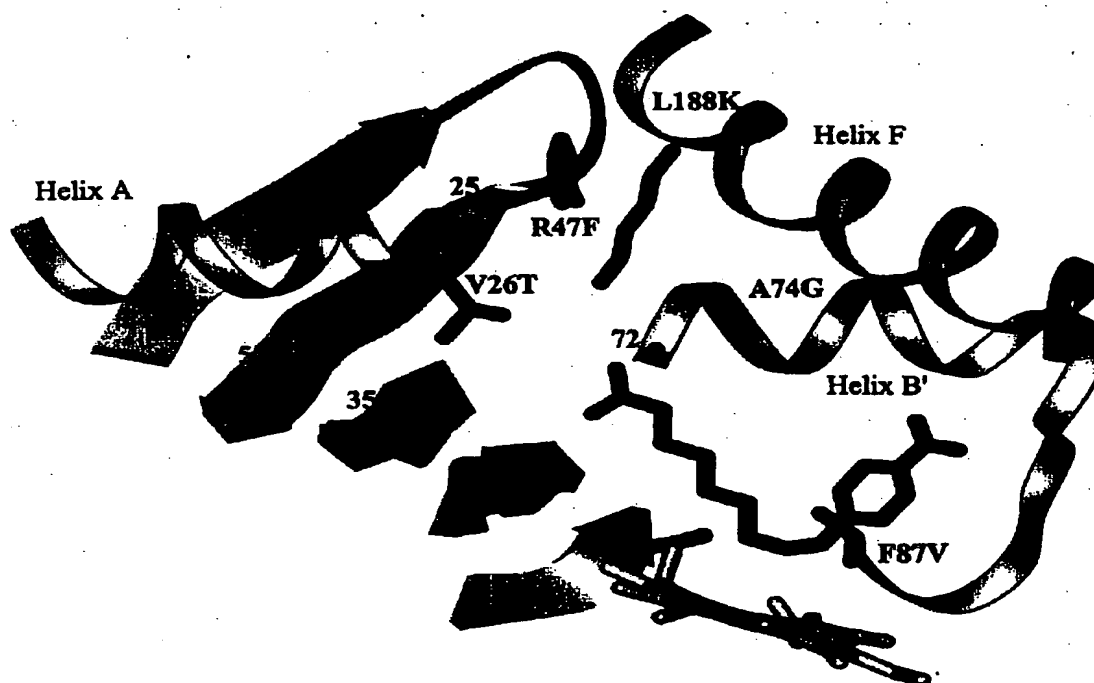


Fig.2

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